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DETERMINATION OF VERTICAL OZONE DISTRIBUTION AT VARIOUS LATITUDES DURING ECLIPSES OF THE MOON

/Following is a translation of a paper which was submitted to the ozone symposium in Brussels (30 August through 1 September 1951) by H. K. Paetzold. This paper was published in the German language in the periodical Journal of Atmospheric and Terrestrial Physics, 1952, Vol 2, pages 183-188, Pergamon Press Ltd, London./

1. Abstract

The vertical distribution of atmospheric ozone may be determined from the distribution of intensity, measured at 6000 Å, on the darkened moon, near the edge of the earth's shadow. It is a characteristic of the method that the ozone distribution at various latitudes may be determined regardless of the point of observation. The usefulness of the method is demonstrated by spectrophotometric measurements made during four eclipses of the moon. The ozone distribution thus obtained correspond to results obtained directly by balloon ascents.

2. Body of Paper

It is known that, during a lunar eclipse, sunlight which passes through the earth's atmosphere is refracted into the area of the earth's umbra. That light which passes through deeper layers of air is directed further into the shadow area on the moon's surface, meaning that the point illuminated by this light has a greater distance γ' from the geometrical limits of the darkened area. A sprectral absorbing layer lying in the earth's atmosphere, and the vertical limits of its extent, should therefore be detected by measuring its absorption in dependence upon γ'. In this way we can determine the vertical ozone distribution for various geographic latitudes of the earth according to the apex angle at which the illumination distribution on the darkened moon are read perpendicular to the edge of the shadow. The measurable apex angle depends upon the path of the moon through the earth's shadow, but is independent of the geographical location of the observation point on earth.

In order to be able to determine ozone absorption in this manner, we must know the normal distribution of illumination on the periphery of the earth's shadow on the moon with the atmosphere free of ozone. This can be calculated with a photometric theory of lunar eclipses developed by F. Link (1). According to my own measurements (2), the agreement between observation and theory in the spectral areas free of ozone absorption is so complete that the latter can serve as a basis for ozone measuring. During these observations and those of other authors (1), (3) and (4), an additional reduction of the light by 90% was actually observed in the area of the Chappuis Bands, which can only be due to ozone. (Note: as the author was able to show (5), this strong absorption is also the reason for a characteristic greenish coloring of a narrow zone along the edge of the shadow. Through this "green zone" on the edge of the earth's shadow on the moon, the atmospheric layer of ozone can be detected with the naked eye.)

Theoretically, therefore, the vertical ozone distribution at latitudes of the earth which were properly oriented to the moon could be determined. Experiments which have been undertaken so far in this direction (1), (3) have not been able to progress beyond the starting stage, however, for the evaluation of the observations is made difficult by the fact that the sun is not a point light source, but rather appears as a disk 32' in diameter from earth or the moon. A point lying in the area of shadow on the surface of the moon is therefore not illuminated from a single light ray, but rather by a pencil of rays of considerable diameter, which naturally tends to blur the calculation of the ozone distribution somewhat. For an approximation of this latter influence, the average ozone mass $O^{*}(\gamma')$ through which a pencil of light rays travels was computed for three given ozone distributions $\varepsilon(h)$. (Note: In the following, all values referring to the pencil of light rays will be indicated with * .)

These three ozone distributions are shown on the left in Illustration 1. They have basically differing characteristics; namely, subdued, pronounced and double maxima. The corresponding curves on the right in Illustration 1 show the dependency of the average ozone mass $O^{*}(\gamma')$ upon the distance γ' of the respective point illuminated by the pencil of light rays from the edge of the shadow ($\gamma' = 0$). It can be seen that, despite the blurring due to the divergence of the pencil of light rays mentioned above, the difference in the course of the plotted curves is so great that the general condition of ozone distribution can still be deduced.

To be sure, the actual derivation of the unknown ozone distribution $\varepsilon(h)$ from the measured function $O^{*}(\gamma')$ in closed analytical form is not possible. It would be solved if the ozone mass $O(h_0)$, through which a single ray passing through the atmosphere tangentially at a minimum distance h_0 from the earth's

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surface travelled were known (see Illustration 2). With a known ozone distribution $\varepsilon(h)$, this ozone mass $O(h_o)$ is given by:

$$O(h_o) = \int_{-\infty}^{+\infty} \varepsilon(h)\, d\,s, \tag{1}$$

where $d\,s$ indicates an element of the path of the single ray traveling from B to A in Illustration 2.

If the following value from the triangle drawn into Illustration 2 is substituted for $d\,s$ we obtain: (refraction can be discounted here)

$$O(h_o) = \sqrt{2a} \int_{h_o}^{\infty} \frac{\varepsilon(h)\, d\,h}{\sqrt{h-h_o}} \; . \tag{2}$$

If, as in this case, $\varepsilon(h)$ is the sought function, then Equation (2) represents an abelian integral equation for $\varepsilon(h)$, the solution of which is:

$$\varepsilon(h) = -\frac{1}{\pi\sqrt{2a}} \int_{h}^{\infty} \frac{\left(\frac{dO\;(h_o)}{d\,h_o}\right)}{\sqrt{h_o - h}}\, d\,h_o \; . \tag{3}$$

From the average ozone mass $O^*(\gamma')$, determined through observations, it is now relatively easy to derive $O(h_o)$ by means of the following technique: in the place of the variable γ' in $O^*(\gamma')$, we introduce h^* (the minimum distance from the surface of the earth for a single ray which travels through the same air mass as does the center of the pencil of light rays), so that we have the new function $O^*(h^*)$ in place of $O^*(\gamma')$. This substitution for γ' is suggested by the fact that, for low altitudes, the functions $O(h_o)$ and $O^*(h^*)$ approach each other more and more. For at low altitudes, the entire pencil of light rays passes the ozone layer below its maximum. In this case, computation show that the masses of ozone travelled through by each individual ray in the pencil of light rays vary relatively little, in contrast to the situation at greater altitudes. For this reason, the mass of ozone travelled through by the single ray in the center of the pencil of light rays is very nearly equal to the average ozone mass $O^*(\gamma')$. The same applies in reference to the Rayleigh extinction. This effect is further supported by the fact that with

decreasing altitude the vertical diameter of the pencil of light rays also decreases, so that it finally approximates the single ray. Illustration 3 demonstrates this relationship for the three ozone distributions shown on the left in Illustration 1.

Below 10 kilometers, the ozone masses $O^*(h^*)$ traversed by the average ray in the pencil practically coincides with the sought function $O(h_o)$, whereas for greater altitudes these two functions vary increasingly. It is therefore possible, when progressing from lesser to greater altitudes, to derive $O(h_o)$ from $O^*(h^*)$ in stages by checking and improving the respective extrapolation through back-computing.

In order to test the reliability of the method, the respective ozone distribution was derived in reverse via the above method from the computed mean ozone masses of curve 1 of the left hand portion of Illustration 1. The control points obtained, which are marked with stars in Illustration 1, can be seen to lie well along the assumed distribution curves. Minute details are naturally lost due to the above mentioned blurring.

An evaluation of a measurement of the lunar eclipse of 6-7 October 1942 (2) using this method indicated a diminishing amount of ozone above 45 kilometers. This corresponds to the prevailing theories as to the atmospheric ozone layer and agrees with the measurements which were found with the American V2 rocket.

Also available are spectral-photometric measurements by Link (1), Danjon (3) and Barbier & associates (4) which could be evaluated with the described method of determining ozone distribution. The resulting mean ozone masses $O^*(p')$ are shown on the left of Illustration 4. The corresponding ozone distributions derived with this method are shown on the right of Illustration 4.

Table 1 also gives the data for the total amount of ozone (ozone value), for the altitude of the maximum concentration of ozone and — particularly characteristic for the described method — the geographic latitudes to which the measurements apply, based upon the apex angle on the moon. Number 4 refers to the case already evaluated by the author (2).

As we can see, the ozone distributions as obtained from the lunar eclipses correspond to direct measurements made during balloon ascents. The ozone value of 0.22-0.33 cm agrees with values obtained through other methods. According to Table 1, this value averages higher in south polar latitudes than in equatorial latitudes. At the time of these observations, the spring season prevailed over the southern hemisphere, so the higher ozone values of spring are indicated here for the higher latitudes. Table 1 shows no corelation between latitude and differences in maximum ozone concentration.

Table 1

No in Illustr 4	Date of eclipse	Geographical latitude	Maximum height of sun	Ozone value cm	Altitude of ozone maximum km
1	16 Oct 1921	60° S	37°	0.33	19
3	26 Sep 1931	0°	90°	0.26	20
2	2 Mar 1942	20° N	63°	0.22	18
4	6 Oct 1949	65° S	44°	0.25	21

Vertical ozone distribution, as it would be computed based on the photo-chemical balance, is greatly disturbed by vertical and horizontal exchange of air. The vertical exchange seeks to establish a quantity ratio of ozone/air which is constant with the altitude. In Illustration 5, therefore, this quantity ratio ozone/air for the four distributions obtained during lunar eclipses (from Table 1) is presented. For comparison, distributions obtained in three balloon ascents at Stuttgart and Weißenau (about 48° N) are shown in Illustration 6, curve 4 in this illustration showing the curve computed according to the photo-chemical balance with the sun at an elevation of 45°. As can be seen, the variations in the ratio ozone/air were so great that they completely cancelled out any variations due to the elevation of the sun.

The few measurements shown here demonstrate the fact that the described method can contribute to obtaining a sufficiently large, widely distributed amount of observational data on the vertical distribution of ozone. For this reason, a few instructions for conducting such measurements are given.

Sufficient for the observations are color filter photographs of the darkened moon at 6000 Å, the maximum for the Chappuis bands of ozone, and also for control and possible elimination of additional influences (mist, periodical abnormal opaqueness of the stratosphere, etc), at 5000 and 4000 Å. With these wave lengths, disturbances caused by the bands of atmospheric oxygen and the weak blue-absorbing layer (1), (2) at 100 kilometers in altitude need not be feared. The spectrally varying albedo of the surface of the moon must of course be eliminated through comparison photographs of the undarkened moon. A more detailed presentation of the method and a discussion of the possibility of errors has appeared in Zeitschrift für Naturforschung (9).

3. Summary

The distribution of atmospheric ozone can be determined from the distribution of illumination intensity on the darkened moon perpendicular to the edge of the earth's shadow, measured at 6000 Å. A characteristic of this method is that the ozone distribution at various latitudes on earth can be determined regardless of the location of the observer. The usefulness of the method is shown in connection with four measurements recently obtained by spectral photometric methods during lunar eclipses. The ozone distributions determined in this way agree with those obtained directly in balloon ascents.

4. Bibliography

(1) F. Link, Bulletin of Astronomy, 1932, Vol 8, page 77. (2) H. K. Paetzold, Zeitschrift für Naturforschung (Journal of Natural Research), 1950, Vol 5a, page 661. (3) C. R. Danjon, 1921, Vol 173, page 706. (4) D. Barbier, D. Chalonge and E. Vigraux, Annals of Astrophysics, 1942, Vol 5, page 1. (5) H. K. Paetzold, Naturwissenschaften (The Natural Sciences), 1951, Vol 38, page 544. (6) F. W. P. Goetz, Berichte des Deutschen Wetterdienstes, US Zone (Reports of the German Weather Service, US Zone), No 11, page 7, 1949. (7) E. Regener and V. H. Regener, Physische Zeitschrift (Journal of Physics), 1934, Vol 35, page 788. (8) E. Regener, H. K. Paetzold and G. Pfotzer, Naturwissenschaften (The Natural Sciences), 1950, Vol 37, page 559. (9) H.K.Paetzold, Zeitschrift für Naturforschung (Journal of Natural Research), 1951, Vol 5a, page 639.

FIGURE APPENDIX

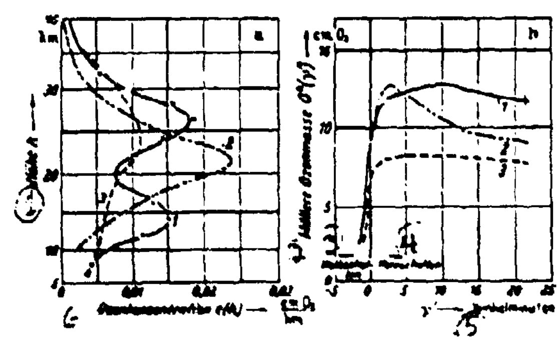


Illustration 1a & b. a. Ozone distribution. 1 = Goetz (6), reverse effect; 2 = Paetzold (2), lunar eclipse of 6 October 1949; 3 = E. and V. H. Regener (7), 31 July 1934.
b. Average ozone mass $O^*(\gamma')$, which is traversed under various conditions of ozone distribution by the pencil of light rays in Illustration 1 (same numbering system).
(Note: the considerable difference between curves 1 and 3 corresponds to an intensity factor of 2 at the maximum Chappuis band (6000 Å).)
Legend: 1 altitude; 2 Average ozone mass; 3 penumbra; 4 umbra; 5 minute of angle; 6 ozone concentration

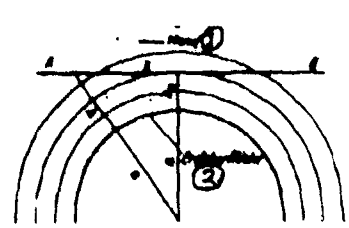


Illustration 2. Path of a single ray in the atmosphere (schematic).
Legend: 1 Moon 2 Surface of the earth.

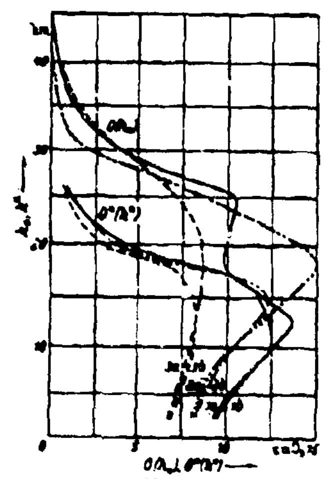


Illustration 3. Curves 1a, 2a, 3a show the ozone mass $O(h_o)$ through which a single ray passes, given the masses 1, 2, 3 in Illustration 1, left. Curves 1b, 2b, 3b show the ozone mass $O^*(h^*)$ traversed by the central ray of a pencil of light rays. Note the almost complete coincidence of curves $O(h_o)$ and $O^*(h^*)$ below 10 km.

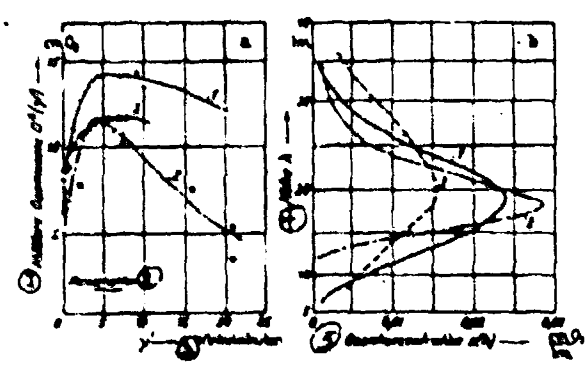
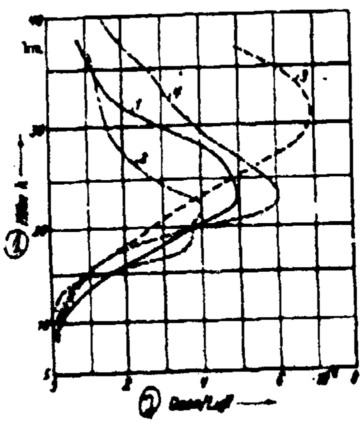


Illustration 4a & b. a. Average ozone mass $O^*(\gamma')$ according to the spectral photometric measurements on the surface of the darkened moon. 1 = 16 Oct 1921 (3); 2 = 2 March 1942 (4); 3 = 26 Sept 1931 (1). b. Vertical ozone distribution according to the average ozone masses in a. (Legend next page)

Legend to Illustration 4a & b:

1 Average ozone mass
2 Umbra
3 Minutes of angle
4 Altitude
5 Ozone concentration



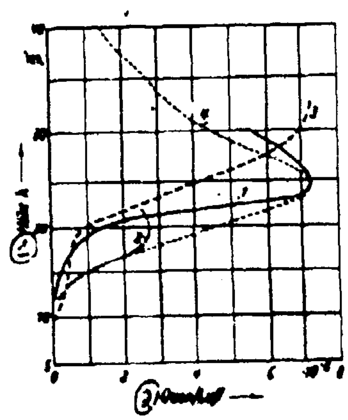


Illustration 5. The quantity ratio ozone/air after lunar eclipses. 1 = 16 October 1921; 2 = 2 March 1942; 3 = 26 September 1931; 4 = 6 October 1949.

Illustration 6. The quantity ratio ozone/air according to balloon ascents. 1 = 18 February 1950 (8); 2 = 26 June 1934 (8); 3 = 31 July 1934 (7); curve 4 was computed according to the photochemical balance for a height of sun of 45°.

Legend: 1 Altitude
2 Ozone/air